EXTRACTION OF HIGH CHARGE ELECTRON BUNCH FROM THE ELSA RF INJECTOR – COMPARISON BETWEEN SIMULATION AND EXPERIMENT

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Abstract

A new scheme based on a photo-injector and an RF linear accelerator operating at 352 MHz has been recently proposed as a versatile radiographic facility. Beam pulses of 60 ns duration containing 20 successive electron bunches that are extracted at 2.5 MeV from a photo-injector are accelerated through the next structure to the final energy of 51 MeV. Bunches carrying 100 nC are required for this purpose. As a first demonstrating step, mora than 50 nC electron bunches have been produced and accelerated to 2.5 MeV with the 144 MHz ELSA photo-injector at Bruyères le Châtel. For this experiment, we compare the results and the numerical simulations made with PARMELA, MAGIC and MAFIA codes.

INTRODUCTION

A proposal for the project named RX2 has been made in view of producing high-flux of short X-ray pulses from a very intense 50 MeV electron beam impinging a high Z material production target. The facility consists of a photo-injector followed by a linear accelerating structure. The beam is finally tightly focused to the target. The 60-ns electron pulse is made of 20 bunches repeated at 352 MHz. Each bunch of 100 ps duration is issued from the photo-injector and carries a 100 nC charge. Several simulation codes have been used to design the photo-injector: PARMELA [1], MAGIC [2], MAFIA [3] and M2V [4].

The space-charge limit is the maximum amount of charge that can be extracted from a gun (at fixed beam size and time duration). This limitation happens when the field induced by the extracted charges (space-charge field) cancels out the gun acceleration field on the cathode. In a stationary 1D model, this is known as the Child-Langmuir current density limit. In the RX2 gun, this limit calculated with the codes [1], [2], [3], [4] is about 600 nC within 20% dispersion from code to code (figure 1). According to these simulations, the RX2 gun 100 nC working point is much lower than the space-charge limit.

To ensure that one can rely on the space-charge limit predicted by the codes, we decided to validate these codes against experimental measurements. In this paper, we present the space charge-limit measured on the ELSA RF photo-injector [5] and we compare it to the code results.

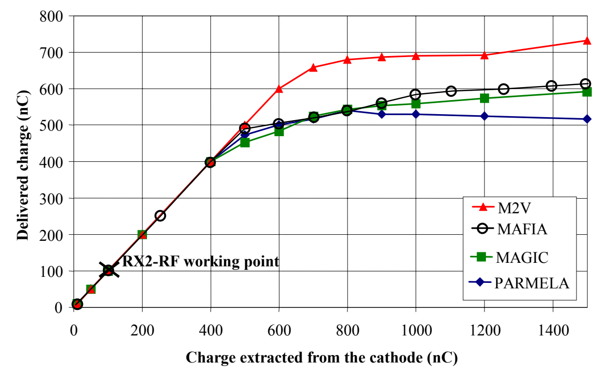

Figure 1: Prediction by four codes for the delivered charge as a function of the expected charge produced from the photo-electric effect. RX2 working point is well below the space charge limit.

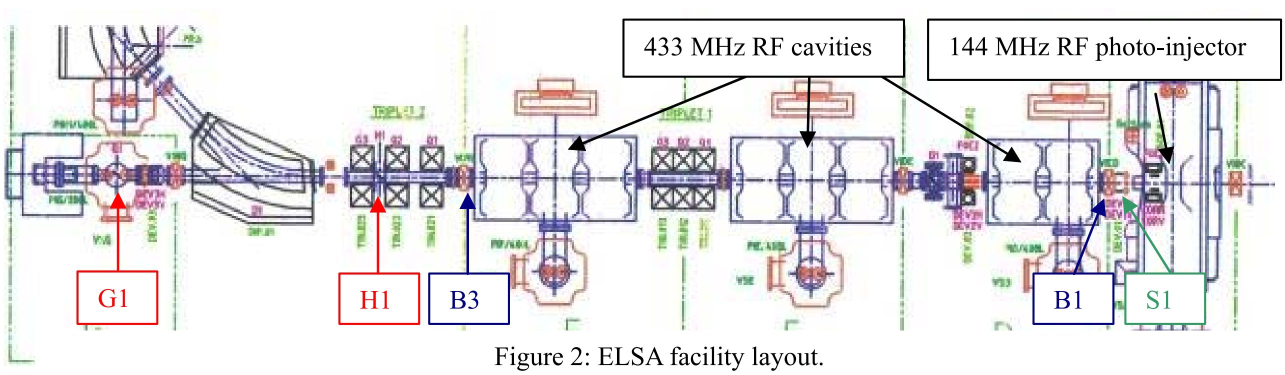

Figure 2: ELSA facility layout.

ELSA LAYOUT

The ELSA layout is presented on figure 2. It is made of a 144 MHz photo-injector delivering 2.5 MeV bunches, followed by three 433 MHz accelerating cavities (not powered in this experiment), focusing elements (triplets, solenoids) and a set of steering coils. The beam reaches currently a final energy of 18 MeV. S1 stands for the extraction solenoid coil. The bunch absolute charge is measured at H1 with a current transformer and at G1 on a Faraday cup. Distance between the photo-cathode and G1 is ~7 m. B1 and B3 are beam position monitors (BPM). By summing the four antenna signals BPM's deliver a signal proportional to the bunch charge. Then, after calibration, they have been used to measure the absolute charge.

CALIBRATION OF BPM's FOR CHARGE MEASUREMENTS

The signals obtained on each of the four BPM antennas are summed. The sum signal is amplified in a logarithmic amplifier before being transported along a 30 m coaxial line to an oscilloscope where the signal is measured through a 50 Ω load (figure 3).

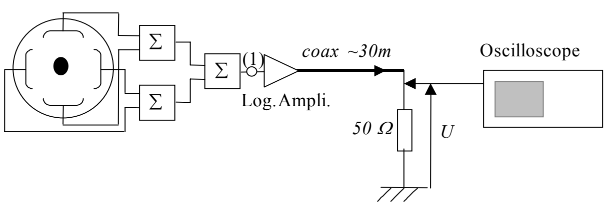

Figure 3: Signal measured on a BPM.

The voltage U delivered by the log-amp depends on the charge Q. More precisely, Q should be proportional to: $10^{\alpha U/20}$, where α is the slope of the log-amp in dB/V. Actually, this slope shows some variation in the range of the log-amp, and it is worth to replace the term αU by a third degree polynomial (figure 4) resulting from a preliminary characterization of the log-amp with a 1-ns square signal at its input (noted °1 on figure 3).

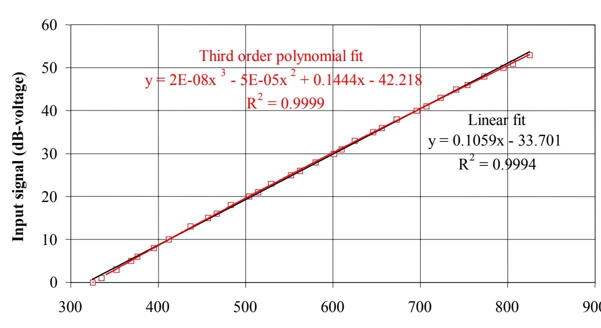

Figure 4: Polynomial fit of the log-amp response signal. Actually, our range of interest stands between 450 and 600 mV.

Thus, the relation between the charge and the measured voltage becomes :

$$Q = Q_0 \cdot 10^{\frac{1}{20}\sum_{i=0}^{3} a_i U^i} .$$

The second factor of the right hand term gives the relative evolution of the beam charge with respect to the measured voltage. The Q_0 coefficient tells the absolute charge.

To determine Q_0, we made some correlated beam charge measurement on B1, B3, H1 and G1 at low charge transport assuming no beam loss (figure 5).

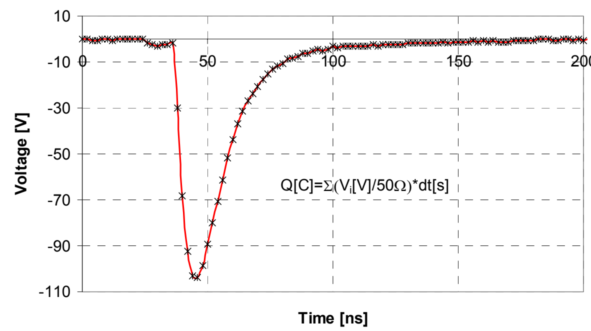

Figure 5: Signal recording for charge measurements: calibration is 1 nC/ 2 10 ^{7} V.s.

At low laser power delivering 0.5 nC per bunch, we measured the signal at the four positions versus the extraction solenoid current. A beam transport with no loss should show in G1 or even H1 some plateau of maximum charge versus the solenoid current. This was experimentally observed as shown in figure 6

Doing the same procedure for four different laser powerings, four Q_0 values are obtained. These four coefficient values, which are in agreement within +/- 5%, are averaged to give the final coefficient.

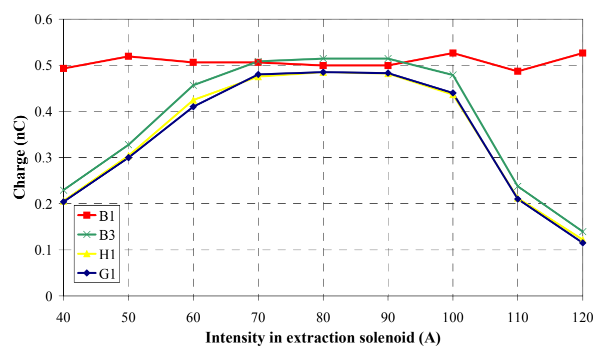

Figure 6: Calibration of the charge at low current: the signals are measured at B1, B3, H1 and G1.

SPACE-CHARGE SATURATION

The laser spot size on the cathode is 8 mm diameter. The "average" transverse beam profile has been modelled by a 2.75 mm sigma gaussian truncated to +/- 4 mm. Its duration is 200 ps FWHM and it has been modelled by a 85 ps sigma gaussian truncated to +/- 170 ps.

In a photo-injector, the number of electrons pulled out of the cathode is proportional to the laser power through the quantum efficiency. When this power is low, all the pulled out electrons are extracted from the gun i.e the total charge extracted is proportional to the laser power. Above a threshold of laser power, the field on the cathode cancels out and reverses due to the remaining pulled out electrons. Only a fraction of these electrons is extracted from the gun.

We have experimentally measured the effective charge extracted from the ELSA photo-injector (B1 viewing station) as a function of the laser power. Typical signal recording is shown on figure 6 Assuming the pulled out charge is proportional to the laser power and that this charge is totally extracted (as long as this charge is low), the extracted charge can be plotted as a function of the pulled out charge.

In figure 7 the experimental results are compared to the simulations obtained with the 3 codes PARMELA, MAGIC and MAFIA. Note that the MAFIA limit (about 50 nC here) is much lower than the 500 nC value obtained in a previous simulation [6] where the emission radius were much larger (15 mm).

The experimental error bars have been deduced from calibration of the charge measurement at B1. It does not take into account the beam parameters stability. The 15% errors bars on MAGIC and PARMELA simulation results come from simulations assuming 10% uncertainties on laser parameters (radial and longitudinal profiles).

MAGIC is in good agreement with the experimental results. MAFIA, even if using the same model as MAGIC, gives a space-charge saturation about 40% lower. This difference have not been explained so far.

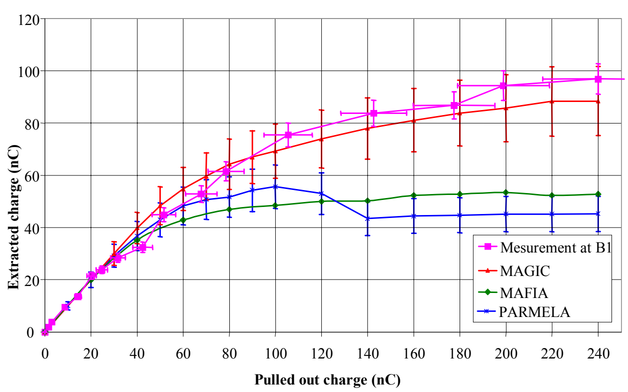

Figure 7: Evolution of the extracted charge from the gun as a function of the charge pulled out of the cathode. Experimental and simulation results are compared.

PARMELA shows some particle losses on the extraction cavity nose as indicated in figure 8 These losses are not observed with MAGIC or MAFIA simulations. During the experiments, we had unfortunately no way to measure the beam losses in the extraction cavity if any.

At full pulled out charge, about 20 nC are lost in the cavity (about 70 nC are extracted from the cathode, as only 50 nC are extracted from the gun). The calculation of the transverse force is clearly different in PARMELA and in MAGIC. This difference could come from a more basic phenomena related to the space-charge model used in PARMELA (indeed the SCHEFF routine assumes no retarded potential and calculated electrostatic field in the beam frame).

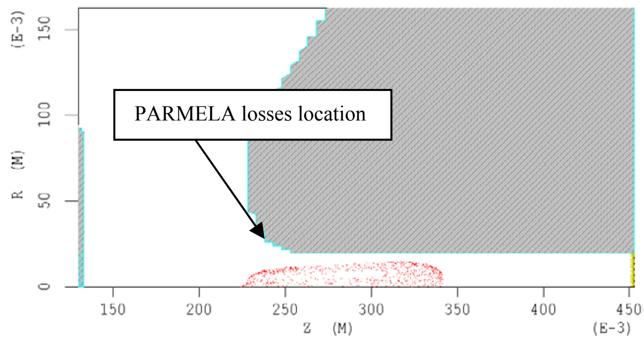

Figure 8: Extracted charge propagation from PARMELA simulations.

We are probably reaching here the limits of PARMELA. At any rate it is still the fastest and the easiest used code at present time. It remains also in good agreement with other codes when used far from the space-charge limit.

CONCLUSION

Different codes (PARMELA, MAGIC, MAFIA and M2V) have been used to design the RF-RX2 accelerator project. These codes predict that the RX2 gun charge retained for operation is much lower than the space-charge limit. To make sure of this, we have measured the space-charge limit on ELSA RF photo-injector and compared it with simulations. MAGIC simulations are in good agreement with experimental results. However MAFIA and PARMELA seem to under-estimate the total charge that can be extracted from the gun.

Moreover, PARMELA predicts beam losses not shown by the other codes. Nevertheless, this discrepancy between code results is much lower than the difference between the space-charge limit prediction for RX2 and does not affect the chosen working point. We are then confident that the RX2 gun can extract the required 100 nC per bunch at 2.5 MeV.

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